THE ACRIM DATA IN THE CONTEXT OF STELLAR VARIABILITY

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ABSTRACT

The ACRIM total-irradiance data from the Solar Maximum Mission have given us a first comprehensive view of solar variability in the stellar sense. Five types of solar variability have been identified thus far. These have small amplitudes, less than a few tenths of one percent, and are at levels generally not yet detectable on other stars. The possible stellar analogs are interesting physically, and in particular may help us to understand solar behavior on longer time scales. This paper describes the ACRIM data from the stellar point of view and comments on the present state of stellar time-series photometry.

INTRODUCTION

Observations from space have now given us a chance to observe solar luminosity variability in the sense of "the Sun as a star." As described below, the observed variations have been rather small, at or just below the threshold of the best ground-based observations. Nevertheless at least five independent mechanisms of variability have been detected in the analysis of ACRIM data thus far, as shown in Table 1 (ACRIM stands for Active Cavity Radiometer Irradiance Monitor).

Table 1
Types of Solar Variability

Mechanism	Time scale	Amplitude
Oscillations	5 min	few parts per million
Granulation	tens of min	tens of parts per million
Sunspots	few days	$\lesssim$0.2% peak-to-peak
Faculae	tens of days	$\lesssim$0.1% peak-to-peak
Solar cycle	11 years	$\sim$0.1% peak-to-peak

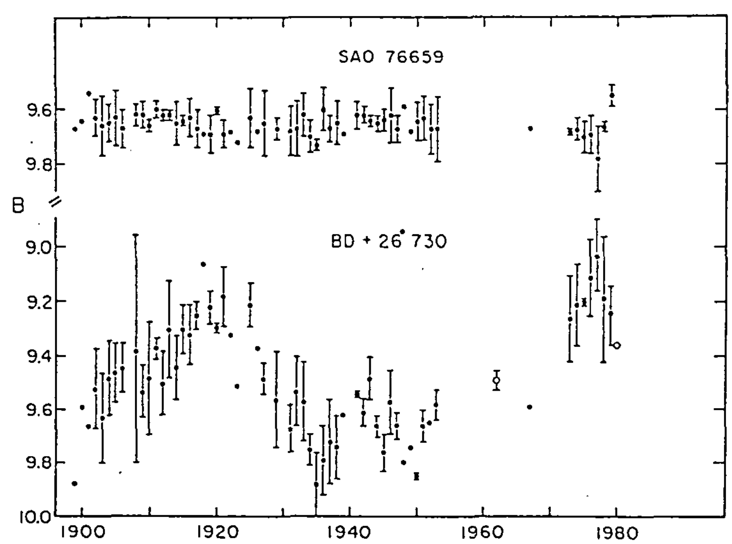
The general approach of the discussion in this review is based on the perspective of the frequency domain. In a power spectrum analysis, one can divide patterns of variability into resonant and broad-band phenomena. The former includes the Hale 22-year magnetic cycle and the p-mode (five minute) oscillations; the latter includes the incoherent variations due to sunspots, granulation, and flares (but note that in Solar Cycle 21 there was a clear tendency for a 155-day periodicity in the occurrence of high-energy flare γ-ray bursts[1]. It is important to note that non-periodic (broad-band) variations are just as important physically, and require just as much explanation, as periodic variations. The question of periodicity may not be particularly important, unless there is a question of resonance in a driven secondary process (*e.g.* in the Earth's weather or climate).

If strongly periodic phenomena do occur (the p-modes being the best solar example) they can be a rich source of precise inputs for reconstructions of interior structure and dynamics via inverse theory.

STELLAR BACKGROUND INFORMATION

There are many types of rapid stellar variability (*e.g.* Warner[2]). Essentially all of the observations of these variations are at amplitude levels considerably larger than those observed on the Sun, and so no strictly comparable types of variation can be studied yet. However we are quite interested in both avenues of information exchange: We wish to learn about stellar physics from the solar case, where we have more sensitive and complete time series of data, and can often identify the direct causes of variability via imaging observations; and we wish to learn about solar physics from the stars, which allow for widely different parameters (stellar age, gravity, chemical composition, rotation rate, *etc.*). The solar analogs are strongest in late-type main-sequence stars, *i.e.* those stars whose parameters approach solar values. These stars may show spottedness (BY Draconis prototype) and flaring (UV Ceti prototype) resembling exaggerated levels of the corresponding solar phenomena. In addition, there are long-term cyclic variations originally discovered by O.C. Wilson[3]. Our interest here centers on how stellar observations can help us to understand the long-term behavior of solar luminosity, since the modern data on total irradiance barely cover one period of the 11-year solar magnetic cycle.

BD+26°730



1. Long-term photographic variability of BD +26°730 and a nearby comparison star (Figure 1 of Hartmann *et al.*, 1981). Error bars represent standard deviations of annual means, and open circles represent photoelectric data.

Hartmann *et al.*[4] have found a late–type star (BD +26°730, dK5e) that shows an enormous cyclic variation apparently associated with a magnetic cycle such as the Sun's; this star shows a full amplitude of some 0.6 mag (roughly doubling in brightness during maximum), whereas the solar amplitude appears to be on the order of 0.1%[5]. The BD +26°730 cycle[4], data reproduced here as Figure 1, illustrates two key points about stellar photometry, namely the difficulty of getting complete time series (see the discussion below of the solar photometry), and of getting adequate precision on longer time scales. Few astronomers wish to spend their valuable observing time endlessly observing the same star, and unfortunately automated observatories (either on the ground or preferably in space) have not reached broadly productive levels yet. Stellar photometric time series are therefore often incomplete, undersampled, and full of gaps, as well as suffering from the problem of atmospheric seeing. Many of these problems are alleviated for high–speed variations[2] (see Kurtz[6] for an example of some of the best stellar data, the relatively complete studies of the Ap "oblique pulsator" stars).

OVERVIEW OF ACRIM DATA

The most complete of the solar total–irradiance measurements come from the ACRIM experiment[7], summarized in Table 2. The standard mode of operation of ACRIM consisted of regular sampling through a mechanical shutter that opened and closed with a 131.072–s cycle. However a long hiatus (December 1980 to May 1984) in the spacecraft's capability for accurate pointing resulted in a period of observation known as the "spin mode." This had greatly reduced sampling and a physically different observing pattern. Another shorter period in late 1989, near the end of SMM's life, was devoted to increased sampling without the shutter in operation. The ACRIM instrument was radiometrically self–calibrated, and contained three identical sensors to permit the monitoring of some kinds of degradation with time of the prime sensor.

Table 2
ACRIM measurements of total irradiance

Period of Observation	February 1980 – December 1989
"Spin–mode" data	December 1980 – April 1984
"No–shutter" data	August, 1989 – November, 1989
Sampling interval	1.024 s
Shutter cycle	131.072 s (25% duty cycle)
Orbital period	96 → 92 min
Digital resolution	12 bits (power measurement)
Principal time–series gaps	shutter cycles (25% on)
	orbital modulation (~60% on)
Spectral response	Bolometric

The analysis of the ACRIM data is still far from complete, but much has been published already[8]; see several papers in these Proceedings).

It is worth noting that of all of the forms of variability, only the largest individual sunspot groups make individually recognizable features in the time series; all of the others are best observed statistically or via Fourier analysis. In particular, flares have not been detected in the total solar irradiance[9], whereas they are quite prominent in the dMe stars of the UV Ceti type. Major solar flares can barely be detected in chromospheric lines in the stellar sense[10]. The ACRIM record also does not appear to show prominences projected against the dark sky at the limb, coronal mass ejections, or comets crashing on the Sun (or at least, studies of the data thus far have not revealed good evidence for these or other mechanisms of variability).

Figures 2–4 show a set of time series of the ACRIM data on successively finer scales, in order to give a feeling for the nature of the variations. Each plot shows the *range* of variation, as indicated by the sample standard deviation, rather than the error of measurement. At each successively-finer time scale, variations become more clearly resolved by the ACRIM sensor, an indication that broad-band variability is present on all time scales, a point confirmed by power spectrum analysis. Figure 5 shows several distribution functions of solar flux levels — these may be compared with the scatter of stellar fluxes on the principle that the time series of brightnesses of one star should have the same distribution as the instantaneously sampled brightnesses of many identical stars undergoing the identical types of variation. This principle is limited, of course, by the lack of a very long time series of solar observations; secular variations not reflected in the modern solar data might yet be present and contributing to the scatter of stellar magnitudes.

LIMITS ON LONG–TERM SOLAR VARIABILITY

We would like to detect or set limits on any secular variability in solar irradiance, *i.e.* variations on longer time scales than even the 11–year variation seen in the ACRIM data. On the longest time scale (Figure 2) the ACRIM variation appears to consist of a flat minimum, upon which the solar maxima appear to be excess amounts of radiation. This is similar to, but less exaggerated than, the variations seen in UV spectral irradiance or the 10.7 cm radio flux.

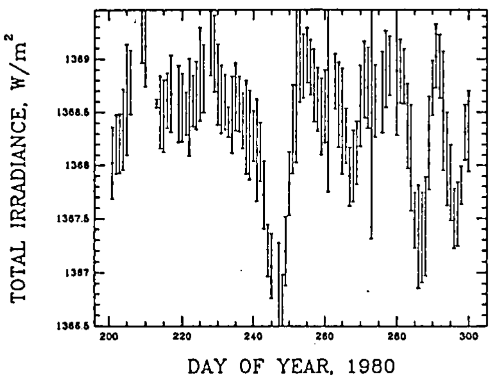
The longer–term variations compete with the five (or more) mechanisms on shorter time scales, which appear as non–random systematic biases in any characterization of a trend. Indeed, Reid[11] pointed out that the sunspot numbers, over the duration of the Greenwich sunspot record, contains a clear secular trend. Foukal and Lean[12] note that this implies a secular trend in the total irradiance if calibrated against the total irradiance data of the past decade.

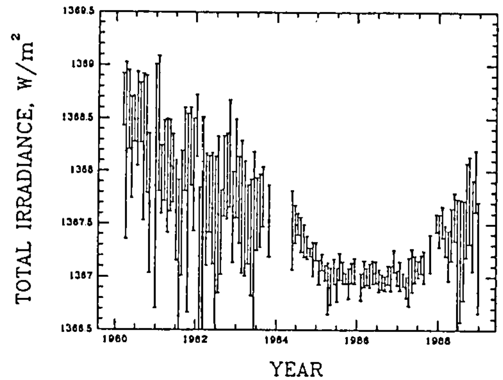
Our best hope for measuring the long–term variability of the Sun directly is to apply model corrections for the known effects. This can only work if the models are accurate, and do not introduce more (or less–well–understood) errors than they remove. Irradiance modeling based upon sunspot areas, 10.7 cm flux, the Ca plage index, and He 10830 Å was quite instrumental in elucidation of the solar–cycle component[5,13].

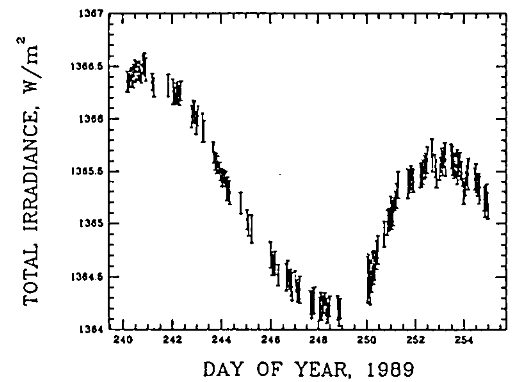
The key to accurate modeling lies in getting better diachronous (synoptic) data. Ground–based data must be improved, and we must urge that NOAA and NASA establish space–based systems for diachronous data collection. At present, the ACRIM data obtained over the "standstill" at solar minimum can only limit any secular trend only at approximately 0.1% per year, not competitive with limits established by ground–based observations. The careful application of total–irradiance models to the ACRIM data can provide stronger limits to secular trends from this same data set, but analysis along these lines has not yet been carried out. Improvements in the diachronous data collection (plus of course a continuation of total irradiance measurements from space) would make this approach quite attractive for the next solar minimum period.

CONCLUSIONS

From the 27–day means of Figure 2, we can already infer that the cyclic variation of a star such as BD +26°730 differs from that of the solar type, in that the cyclic term appears much larger relative to the short–term contributions of the activity. It is also known that more rapidly rotating stars exhibit an anticorrelation of the cyclic and short–term modulations, rather than a direct correlation



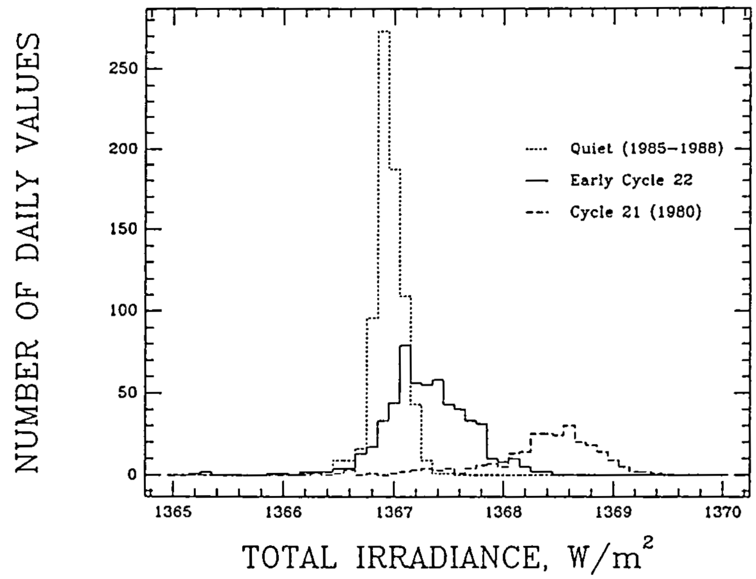




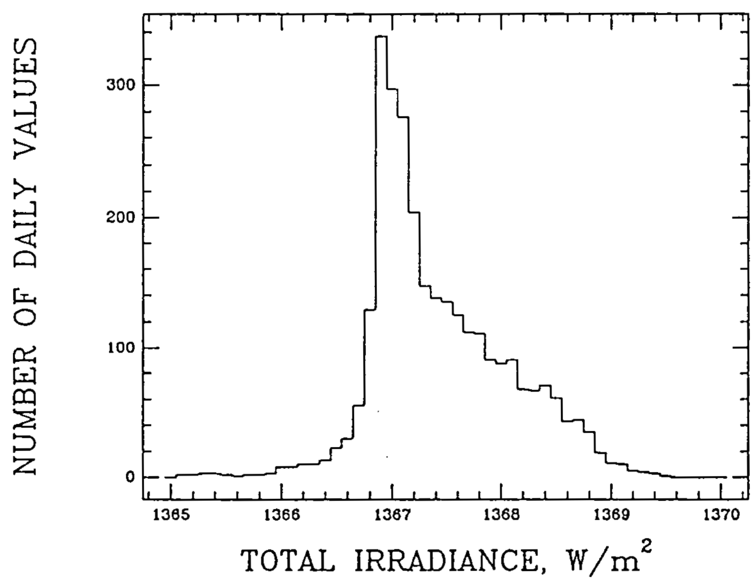
2. (Left) Time series of ACRIM data in 27-day intervals. As in Figure 1, the error bars represent standard deviations of the data, rather than true error estimates, and might better be called "range bars." Much of the variation in the solar maximum periods is due to the direct effects of sunspots.

3. (Center) Representative time series of ACRIM daily data. Again, the error flags are sample standard distributions showing the full range of fluctuation. Figures 2–4 have the same amplitude range of 3 W/m^2.

4. (Right) Representative time series of orbital means of ACRIM data (preliminary version; the final analysis of these no-shutter data will differ from the values shown here). Again, the error flags are sample standard distributions showing the full range of fluctuation. The data show a high degree of variability associated with the disappearance at the limb of still-growing sunspots of active region # 5669, but the data distribution is approaching a normal distribution of errors on this one-orbit (~55-minute) time scale.



5. Distributions of solar total irradiance values from the ACRIM data for three different epochs, excluding the special data (spin mode and no–shutter mode). The 1980 data show a well–defined skew due to the dips in the time series resulting from sunspots. Such distributions can be compared with the results of photometry of solar–type stars under the "equivalence principle" (*e.g.* Baliunas, 1990) of time–series and multiple–star photometry. Because the solar variations are so small, no direct photometric comparison has yet been possible.



6. Distribution of all daily values of ACRIM total irradiance. This distribution includes the spin–mode data. Note the prominent narrow peak in "bolometric luminosity" values produced by the standstill of total irradiance during the sunspot minimum.

as shown by the Sun.

The histograms in Figures 5 and 6 can also be compared with stellar photometry in the Ca K 1–Å index or other chromospheric indicator[14], but only if appropriate calibration can be made from solar observations. Such comparisons will always be uncertain to the extent that the physics may differ, thus destroying the calibration based upon solar processes.

Better stellar time–series photometry clearly would make all the difference in exploiting the analogous forms of variability, since this would allow us to make direct comparisons rather than going through a chromospheric proxy of uncertain calibration. This will require drastic improvements in sensitivity and observational duty cycle; this suggests observations from space[15] or else substantial improvements in ground–based photometry. The use of frame normalization of CCD sensors is very promising in this regard[16,17,18].

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